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Laser cooling, evaporative cooling and Bose-Einstein condensation

Pradip N Ghosh
Department of Physics, University of Calcutta, 92, A.P.C Road, Kolkata-700 009, India
E-mail : png@cubmb.ernet.in

Abstract : Laser radiations are used to slow down atoms by the process of momentum transfer. This leads to reducing the temperature to microkelvin region. Gas phase atoms are trapped by using magnetic fields. The recent advances have led to the realization of the dream of physicists of confining the atoms and reducing their velocities to the limit imposed by quantum mechanics. A number of new experiments are possible with the cooled and trapped atoms and ions that would be useful to solve many problems of theoretical physics. Further cooling by the process of evaporative technique has led to the observation of Bose-Einstein Condensation predicted by Einstein and Rose nearly seventy-five years ago. A brief review of the method of laser cooling, magnetic trapping and evaporative cooling methods used for obtaining ultracold atoms are discussed It is possible to obtain temperature in the nanokelvin region without using cryogenic methods thus simplifying the experimental methods to a great extent.

Keywords : Laser, evaporative, cooling, B-E condensation.

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1. Introduction

The feeling of hotness or coldness is relative to the temperature of the surrounding. Every object tries to be in thermal equilibrium with its environment. If gas molecules are filled in a container at room temperature they move at random in all directions inside the container and attempt to be in thermal equilibrium with the container. They have velocities of the order of a few hundred meter/second. Because of the random nature of motion average velocity $\langle v \rangle = 0$. But $\langle v2 \rangle$ is positive and according to kinetic theory the absolute temperature is proportional to $\langle v2 \rangle$. Temperature is normally defined for a bulk material and is the average property of the system. However, temperature is an expression of kinetic motion of the particles. Hence the kinetic energy of a particle may define the kinetic temperature. Below the freezing point of water we have the domain of so-called low temperature physics where we have the phenomena of superconductivity and superfluidity. The quantum laws can explain the zero resistance of a conductor or a superfluid climbing up a wall with zero viscosity. At high temperature and low density everything is in the form of vapour. But at low temperature and high density everything is in condensed state. Liquid helium is not a Bose condensate since it is not a gas but a liquid with strongly interacting atoms. For many years people tried to achieve BEC in a gas of atoms. The attempt is to cool the atoms to sufficiently low temperature *i.e.* to have a very low velocity without allowing them to condense. For this purpose we can first review the basic process of condensation. Condensation starts on the walls or some dust particles or impurities in the system. If the system is very clean and the atoms are not allowed to touch the walls there will be no condensation. We have to reduce the velocity of the atoms under this condition in order to obtain low temperature gas phase atoms.

2. Cooling the atoms in the gas phase

For cooling the atoms in the gas phase one has to keep them at low density so that there are no three-body collisions, which induce molecule formation. Any molecule that may be formed may act as a nucleus of condensation. If three atoms come together two of them collide to form the molecule while the third takes away the energy. At low densities the

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chances of three body collisions are rare and so possibility of condensation is remote. Th.e first step to cool down the atoms at low density is to use laser cooling [1]. When the atoms are sufficiently cooled one can use the technique of evaporative cooling. The detailed description of the process of laser cooling is given in Ref. 2. However, we present a brief review of the basic principles. We also describe the method of evaporative cooling originally suggested for observation of BEC in hydrogen atom.

Laser cooling :

Any ray of light falling on matter exerts a pressure. We do not feel the effect of sunrays falling on our body because our mass is too high and the momentum exerted by the light photons is too small. If the photon falls on an atom, which has a resonance frequency equal to that of the photon, the atom absorbs the photon: If two particles with different momenta coming from opposite directions collide and after the collision the second particle is absorbed by the first then from the law of conservation of momentum the momentum of the second particle is transferred to the first and consequentially the first particle is decelerated. Similarly, if an atom resonantly absorbs a photon coming from the opposite direction the momentum of the photon is transferred to the atom and the atom is pushed back and loses its velocity. If the atom and the photon are moving in the same direction the atom may be accelerated in the same process. In order to ensure deceleration of the atom the atoms should absorb only the oppositely moving radiation. This is achieved by using Doppler effect. The radiation frequency is detuned to lower than the resonance frequency so that due to Doppler effect the atom will see a higher frequency for the oppositely moving radiation and move closer to resonance (Figure 1). But it will see a lower frequency of the wave if it is coming from the same direction and will go away from resonance.

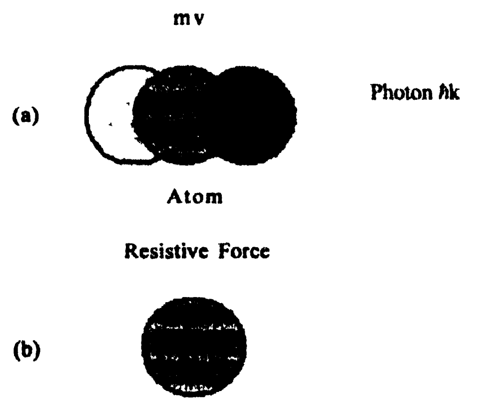


Figure 1. An atom moving with a certain velocity interacts with counter-propagating laser beam. The laser photon is absorbed and transfer of momentum of the photon to the atom leads to deceleration of the atom as indicated in the lower figure.

Hence the possibility of absorbing the oppositely moving radiation is larger. If there are two counter-propagating waves they can be used to decelerate the atoms coming from both directions [1]. After the absorption the atoms emit photons, which may also accelerate them. But spontaneous emission is a random process, so the net change of momentum is zero. But the energy change in the recoil process does not average to zero and may cause heating. This leads to a lower limit for cooling which can be calculated [2]. Thus the process of Doppler cooling can lower the temperature to the order of 100 μK for alkali atoms.

Optical molasses :

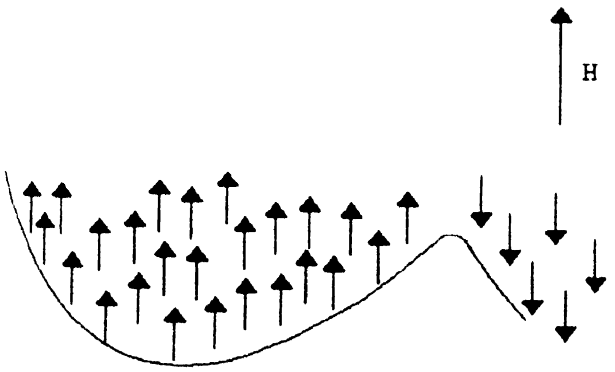
With the help of three mutually perpendicular laser beam one can produce cooling in all six dimensions by reflectin each beam by a mirror. This is called optical molasses sinc the atoms experience a strong viscous force in the thre dimensional space [3]. When a fly falls in a pot of molasse it tries to move out. In whatever direction the fly attempt to move the molasses push them in the opposite direction The poor fly cannot move out. An atom in the optic molasses faces a similar condition, but if it can come out o the molasses it will move with the residual velocity due t its inertia. So one has to find a method to hold them onc they are in the optical molasses. This is achieved by usin a magnetic field [4]. It was found by Phillips and coworker [5] that the optical molasses could produce a temperatur much lower than the Doppler cooling limit. This is a cas where experimental findings surpassed the theoretica predictions.

Sisyphus cooling :

Cooling below the Doppler limit was explained by Dalibar and Cohen-Tanoudji [6] and Ungar *et al* [7] in two separat papers in 1989. Both these papers proposed a new mechanis for laser cooling. They showed that a combination of thre known effects could produce such low temperature. Th three processes are optical pumping, laser polarizatio gradient and light shifts. In the optical molasses the atom are made to climb up energy hills. When the atoms climb u to the top of the energy hills they fall down to the energ valley due to optical pumping and have to climb up agair Sisyphus of Greek mythology had to face an ever-climbin hill with a ball. He never had a chance to climb down. Th energy valleys are produced in the space coordinate by th laser polarization gradient produced by the counte propagating laser beams, optical pumping and light induce shift of energy levels. The reader may refer to an exceller article by Phillips and Cohen-Tanoudji [8]. The atoms fac an ever-climbing hill and have no chance to go down th energy hill. Whenever an atom climbs up the hill it has to do some work; thus it loses energy and gets cooled. The temperature of the order of μK could be reached for alkali atoms in this process. But this is not enough for observation of Bose-Einstein Condensation. Further lower temperature could be obtained by using the simple method of evaporative cooling.

Magnetic trap :

Once the atoms are cooled to μK range of temperature we have to confine them. If the cooling laser is turned off the atoms will start moving apart with their residual velocities and will hit the walls or will eventually fall down under gravity. The cold atoms usually have a velocity of a few centimeters per second. Hence a relatively weak magnetic field may be used to confine them. Alkali atoms have a magnetic moment because they have an unpaired electron. The magnetic moment is in a direction opposite to that of he electron spin. The magnetic moment interacts with an applied weak magnetic field. If the magnetic moment is parallel o the external magnetic field the atom is attracted to the ocal minimum of the field and can be trapped. Thus the nagnetic field can act as a little bowl (Figure 2) and the itoms can be trapped in the bowl [4].



igure 2. An atom with spin parallel to the magnetic field is attracted the energy minimum and an atom with anti-parallel spin is repelled. n RF field is chosen such that it resonates with hotter atoms near the p of the trap. The atoms absorb the photons, the spins are reversed so they are repelled from the trap and are eventually lost from the The frequency can be gradually lowered to get deeper into the bowl to expel more atoms.

Bose-Einstein condensation

osons are particles with integral spins and Fermions have ilf-integral spins. What matters most is that Fermions are ne sort of loners – they do not allow more than one rticle to be in one state. Bosons are more social; they like be together in the same state. Photons are bosons, but e elementary building blocks of matter like electron, proton, on *etc* are fermions. All atoms are made up of a bunch f fermions. If an atom is formed of an even number of nions then it has an integral spin and it is a boson.

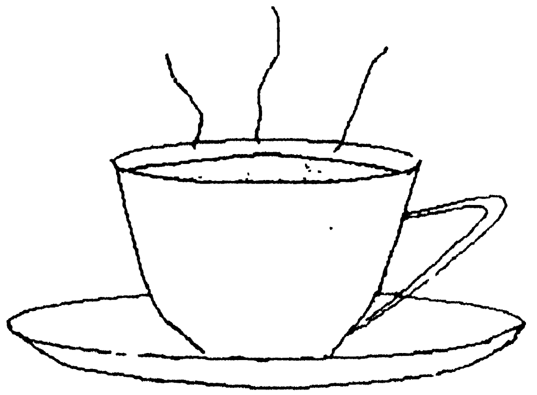
In his 1924 paper Satyendra Nath Bose explained the black body radiation from a hot gas by treating the photons as a gas of identical particles. Einstein was very excited after reading this paper and pointed out that the same rule could be applied to other particles with integral spins. This led to Bose-Einstein distribution. In the same year Einstein predicted that at very low temperature all the atoms in an ideal gas of identical atoms might be condensed to a single lowest quantum state of the system. This large number of atoms locked together in the same state is called the Bose-Einstein Condensate (BEC). This is a system of weakly interacting gas particles all behaving in the same way in a single quantum state. The condensate differs from superfluid helium. The low temperature necessary for obtaining BEC is of the order of nanokelvin and such temperature was attained and BEC was observed for the first time in 1995 in three laboratories [9–11]. In this article we shall discuss the basic principles of achieving this low temperature and the experimental techniques that have been used to observe BEC. In a laboratory where research on BEC is going on one may not find a single cryostat for liquid helium or a single dewar for liquid nitrogen. Atoms are at 300 nK when all the instruments and containers are at room temperature. In order to understand this phenomenon we shall first review our concept of cooling and heating.

Although Bose-Einstein Condensation was first experimentally realized in 1995 on the alkali atoms experimental and theoretical research [12] in this field started much earlier [13]. Initially superfluidity in helium was considered as the possible manifestation of BEC. Experimental attempts to have BEC in atomic gases began with atomic hydrogen in a dilution refrigerator. Magnetic trapping and evaporative cooling methods were developed and successfully used for this purpose. But the tendency of individual hydrogen atoms to form molecules hindered the process of formation of BEC [14,15]. Eventually BEC in spin-polarized hydrogen was observed by the MIT group.

Evaporative cooling :

It is known that a cup of tea cools down by evaporation. The basis physics of evaporative cooling is simple. A cup of tea (Figure 3) can be assumed to contain a large number of tea molecules, which may be a complex mixrure of tea, sugar, milk and water having different thermal energies. An energy barrier at the surface holds the molecules together. The molecules that have enough energy to cross the barrier will leave the cup or they will evaporate. These molecules will have more energy than the energy required for evaporation or the work function of the cup of tea. After the molecules with higher velocity leave the average energy of the remaining molecules become lower. So they have a lower temperature. The process of cooling starts at 373 K and the temperature comes down to nearly 300 K. If we measure the decrease in the level of tea in the cup when it is allowed to cool down, of course, without taking a single sip, we can get an idea of the number of molecules that leave the cup to bring about this temperature change. It will be found that the change is at most 2%. Thus an evaporation of 2% of tea molecules can produce a 20% change of temperature. So the process is indeed very efficient. If we take a cup of tea without any lid it can cool down to very low temperature. But they cannot be colder than the room temperature.

Evaporative Cooling



Evaporation of 2% tea molecules produces a 20% change of temperature !

Figure 3. Evaporative cooling of a cup of tea.

It was shown by Hess 16 that the idea of evaporative cooling could be applied to the atoms confined in a magnetic bowl. In this case we have to take the higher energy atoms out of the bowl so that the rest will be colder. Atoms are first cooled and trapped in the magneto-optical trap (MOT). By using optical pumping all the atoms can be brought to the same spin state (spin up, say) because of the polarization dependent selection rule between the spin states. The atoms are then attracted to the local minimum. If a radio-frequency oscillating field is applied to induce transitions in the atom between the spin up state (attracted to the magnetic trap) and the spin down state (repelled by the magnetic trap) the atoms will undergo a spin-flip transition. If the RF field is tuned to the higher energy side of the magnetic bowl (Figure 2) the atoms having higher energy will first jump the well and will fallout of the bowl. When the atoms from the top of the bowl are removed the radio frequency can be lowered to get deeper into the atomic cloud in the bowl and this will induce more atoms to leave the bowl. The remaining atoms will get colder in the process. When a large number of atoms are expelled from the barrier the barrier potential also gets modified. The process is discontinued when the temperature goes down to nearly 100 nK and only a few atoms are left to form a condensate. This process of cooling is comparable with that in a cup of tea. When we take a sip the hotter tea molecules come out first. In a magnetic bowl the RF field provides sucks the hotter atoms.

Observation of BEC :

Observation of BEC is a major problem. The size of the condensate is of the order of micron and they are optically thick so it is difficult for light beam to pass through it. The BEC atoms are inside a glass chamber and are away from the walls. The chamber cannot be opened. In the initial experiments [9–11] on BEC after the formation of BEC the magnetic field and the cooling lasers were switched off. Because of their velocities the atoms started flying apart. A probe laser having a frequency in resonance with one of the transitions of the condensate atoms was focussed on the atomic cloud. The resultant absorption caused a shadow that was recorded by a CCD camera. The photograph of atomic positions indicated the expansion of the atomic cloud since the moment the MOT was switched off. Hence this exhibits the velocity distribution. The expansion is very slow as the atoms are in the lowest energy state. A sharp peak of atoms (Figure 4) appearing in the centre of the image gives a signature of BEC. The pedestal of the image shows the hotter atoms that have not been Bose condensed

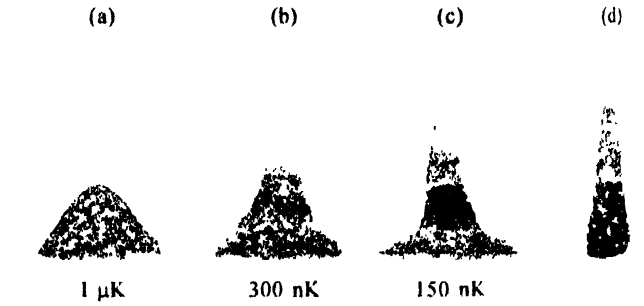


Figure 4. (a) Before the formation of BEC, atoms have a Gaussian distribution; (b) soon after the transition to BEC a spike appears on the Gaussian pedestal; (c) at further lower temperature more atoms form BEC, the Gaussian becomes smaller; (d) finally all atoms are Bose condensed and the Gaussian disappears.

They follow Maxwellian distribution. The two wings of the image may be interpolated and can be fitted to a Gaussian, which can lead to the temperature. The time-dependent measurements after the switching off of MOT shows the rate of expansion of BEC [17] and hence the rate of heating. This process of observation of BEC is destructive since the atoms are lost from the trap.

Bose condensation of gas atoms :

Each atom has an associated deBroglie wavelength λ. An atom is smeared over a distance λ given by $\lambda^2 = (h^2/2mkT)$. At normal temperature this wavelength is much smaller than the average distance between the atoms. Hence there is no overlap of the individual atom and the classical distribution law can describe the gas. When the gas is cooled; the wavelength increases. In an ultra cold gas of identical bosons the deBroglie wave of one atom overlaps that of nearby atoms (Figure 5). So the average distance between the atoms becomes comparable to their deBoglie wavelength.

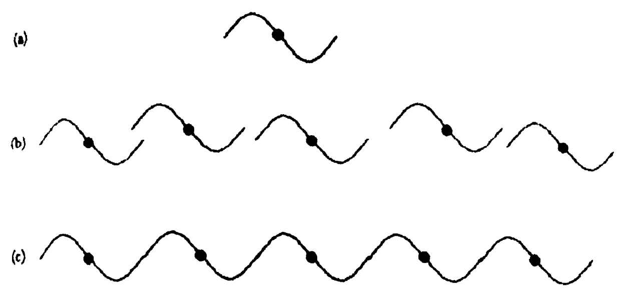


Figure 5. (a) An atom behaves as a deBroglie wave; (b) at low temperature the atomic deBroglie waves come closer together; (c) at critical temperature the average distance between the atoms becomes comparable to the deBroglie wavelength and the deBroglie waves overlap. The system exhibits transition to the BEC phase.

Hence the wave functions of adjacent atoms overlap. As a result the behaviour of the entire system can be described by a single macroscopic wave function. At very low temperature all the atoms fall down to the lowest state, as they do not have enough energy to go to higher energy states. The transition to BEC corresponds to a transition from a set of disordered atoms to coherent matter waves. This is comparable to the transition from incoherent light to coherent laser radiation. All the atoms in BEC behave in a coherent way. The condensate may be considered as a new state of matter, behaving as a macroscopic system of millions of atoms. All the atoms can be described by a single wave function. This is remarkably simple. Interference between two freely expanding BEC's has been observed recently [18]. Two condensates separated by a distance of 50 micrometers were produced by evaporative cooling of sodium atoms in a double well potential produced my magnetic and optical forces as described above. Matter wave interference was observed after switching off the laser and allowing the condensates to expand. This shows that the condensates do indeed have a phase. So it is possible to extract a coherent beam of atoms from a BEC and ultimately may lead to the realization of an atom laser.

Conclusion

A brief review of basic principles of different cooling methods used for experimental observation of Bose-Einstein condensation in atoms is described. Bose-Einstein condensation in a dilute gas of atoms was described in another review [19]. Theoretical developments in the field have shown rapid progress and reviewed recently [20]. The experimental search for BEC in dilute atomic gas started with atomic hydrogen in 1978. But the attempts had a serious problem arising from recombination on the walls and also from molecule formation because of three-body interaction. By using RF-driven ejection technique of evaporative cooling Greytak, Kleppner and their colleagues at MIT could achieve BEC in hydrogen atoms at a temperature of 50 micro Kelvin with a density of 10^{15} atoms/cm^3 Since hydrogen atoms could be probed at much shorter wavelength they used 1S-2S two-photon spectra for observation [21].

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References

[1] T W Hansch and A L Schawlow *Opt. Commun.* **13** 68 (1975)

[2] C J Wineland and W M Itano *Phys. Rev* **A20** 1521 (1979)

[3] S Chu, L W Hollberg, J E Bjorkholm, A Cable and A Ashkin *Phys Rev. Lett.* **55** 48 (1985)

[4] E Raab, M Prentiss, A Cable, S Chu and D Pritchard *Phys Rev. Lett* **59** 2631 (1987)

[5] P Lett, R Watts, C Westbrook, W D Phillips, P Gould and H Metcalf *Phys Rev Lett.* **61** 169 (1988)

[6] J Dalibard and C Cohen-Tanoudji *J. Op. Soc. Am.* **B6** 2023 (1989)

[7] P J Ungar, D S Weiss, E Riis and S Chu *J. Op. Soc. Am.* **B6** 2058 (1989)

[8] W D Phillips and C Cohen-Tanoudji *Phys. Today* (1990)

[9] M H Anderson, J R Ensher, M R Mathews, C E Wieman and E A Cornell *Science* **269** 198 (1995)

[10] K B Davis, M O Mowes, M R Andrews, N J van Druten, D S Druffe, D M Kurn and W H Ketterle *Phys. Rev Lett.* **75** 3969 (1995)

[11] C C Bradley, C A Sackett, J J Tollett and R G Hulet *Phys. Rev. Lett.* **75** 1687 (1995)

[12] F Dalfovo, S Giorgini, L P Pitaevski and S Stringari *Rev. Mod. Phys.* **71** 463 (1999)

[13] A Griffin, D W Snoke and S Tringari (eds.) *Bose-Einstein Condensation* (Cambridge : Cambridge University Press) (1995)

[14] I F Silvera and T M Walraven *Phys. Rev. Lett.* **44** 164 (1980)

[15] Greytak and D Kleppner in *New Trends in Atomic Physics edited by* G Grynberg and T Stora (Amsterdam : North Holland) (1984)

[16] H F Hess *Phys. Rev.* **B34** 3476 (1986)

[17] U Ernst, J Schuster, F Schreck, A Mane, A Kuhn and G Rempe *Appl. Phys.* **B67** 719 (1998)

[18] M R Andrews, C G Townsend, H-J Meisner, D S Durfee, D M Kurn and W Ketterle *Science* **275** 637 (1997)

[19] P N Ghosh *Phys. Education* 17 115 (2000)

[20] F Dalfovo, S Giorgini and L P Pitaevskii *Rev. Mod Phys* 71 463 (1999)

[21] D G Fried, T C Killjan, L Willmann, D Landhuis, S C Moss D Kleppner and T J Greytak *Phys. Rev. Lett* 81 3811 (1998)